Higgs and EW symmetry breaking – a perspective

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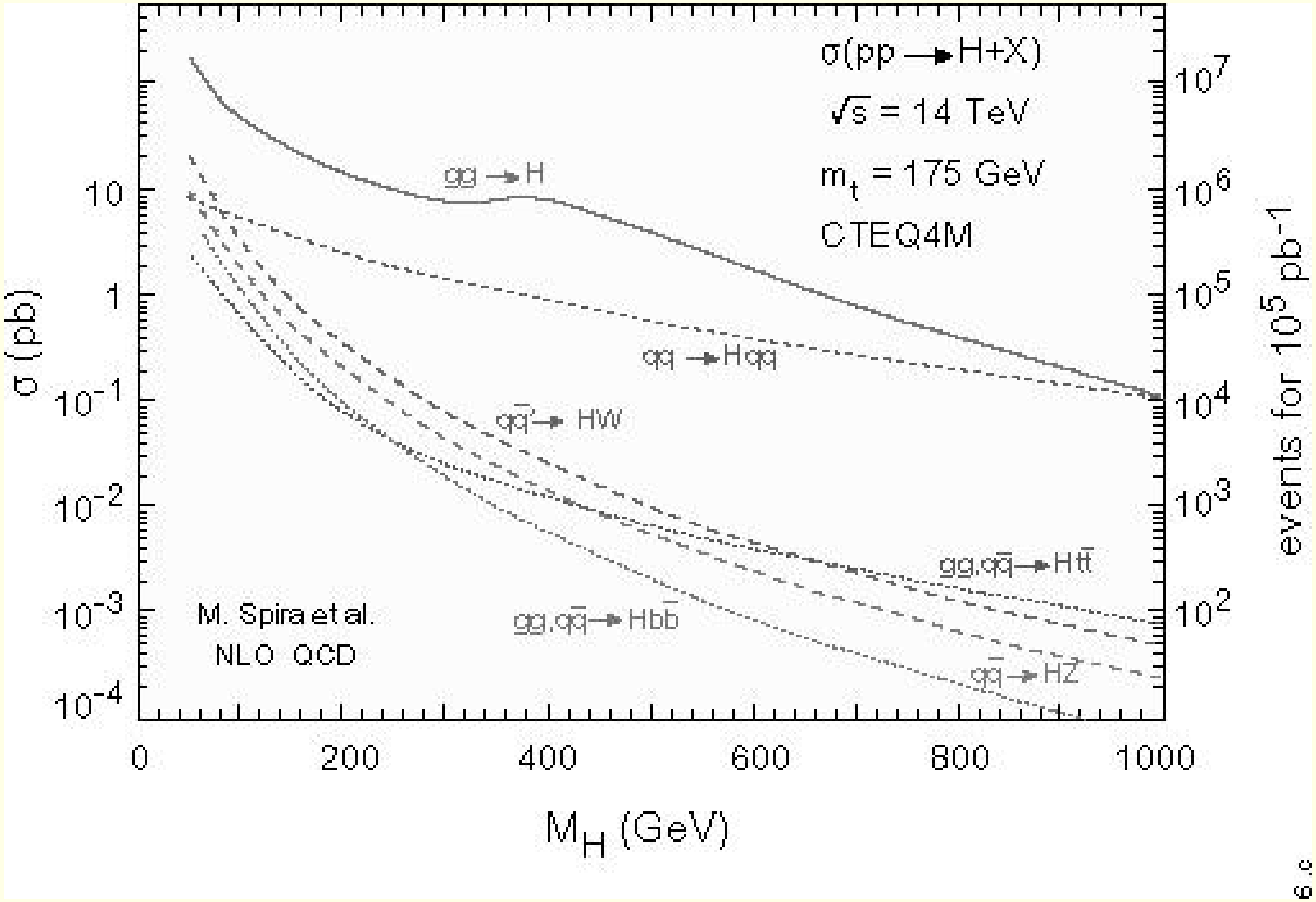
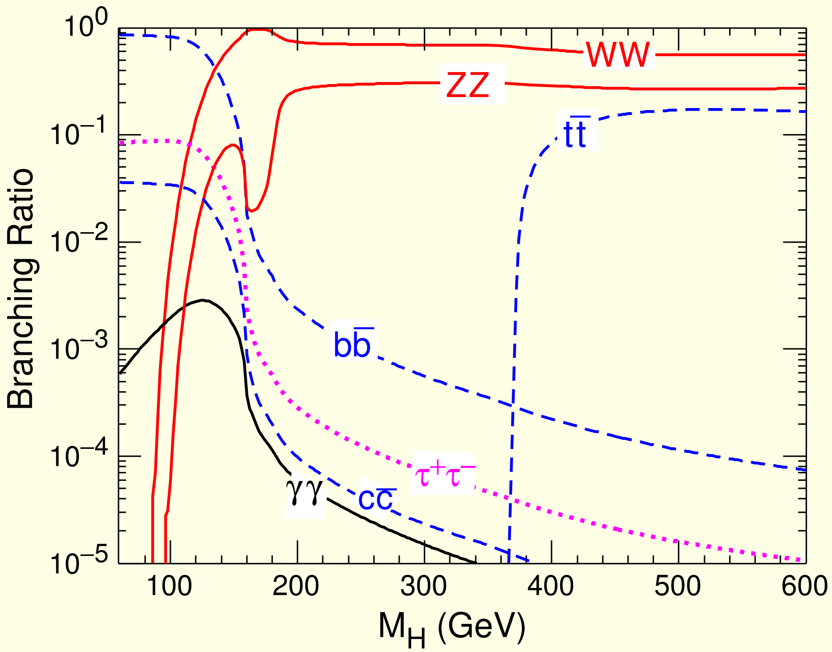
Assumptions and Outline

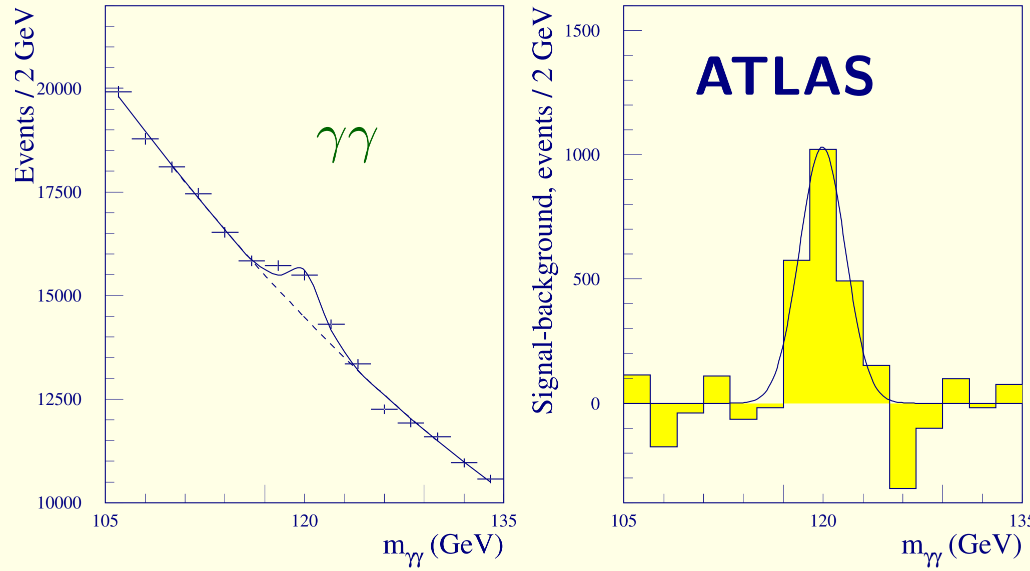
- **Current LHC schedule – Physics run $10\ \mathrm{fb}^{-1}$ starting in spring 2007.**
- **Significant LHC data before NLC begins**
- **Outline**
  What will LHC get?
  LHC upgrade?
  Missing information that NLC must provide

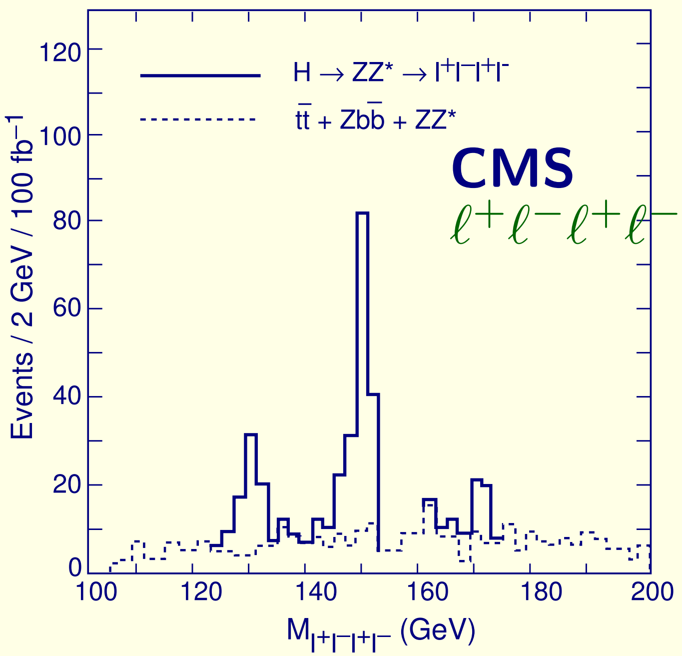
Standard Model Higgs at LHC

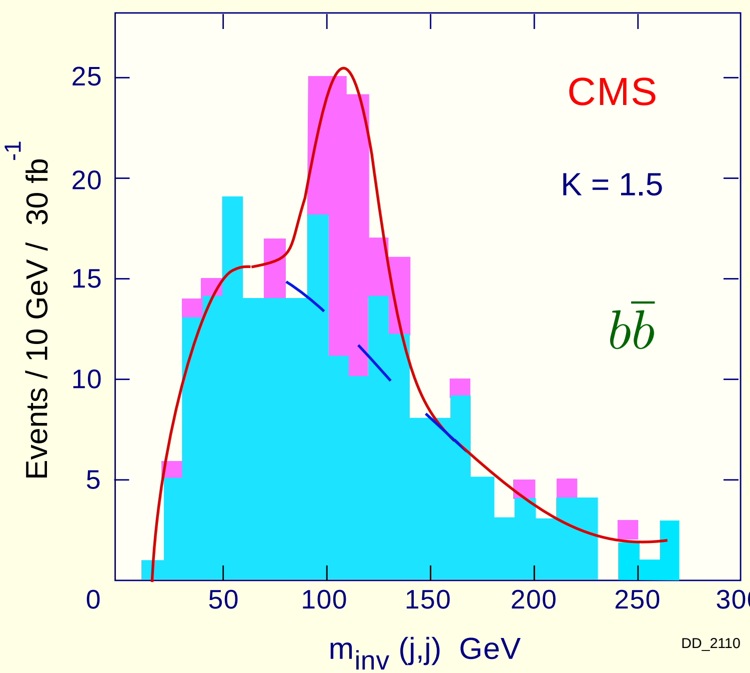


LHC searches/measurements will exploit many production mechanisms and decay modes


Branching Ratio
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
WW
ZZ
$t\bar{t}$
$b\bar{b}$
$\tau^+\tau^-$
$c\bar{c}$
$\gamma\gamma$
100
200
300
400
500
600
M_H (GeV)


Events / 2 GeV
20000
17500
15000
12500
10000
$\gamma\gamma$
105
120
135
$m_{\gamma\gamma}$ (GeV)
Signal-background, events / 2 GeV
1500
1000
500
0
ATLAS
105
120
135
$m_{\gamma\gamma}$ (GeV)


Events / 2 GeV / 100 fb^{-1}
120
100
80
60
40
20
0
$H \to ZZ^* \to l^+l^-l^+l^-$
$t\bar{t}$ + $Zb\bar{b}$ + ZZ^*
CMS
$\ell^+\ell^-\ell^+\ell^-$
100
120
140
160
180
200
$M_{l^+l^-l^+l^-}$ (GeV)


Events / 10 GeV / 30 fb^{-1}
25
20
15
10
5
0
CMS
K = 1.5
$b\bar{b}$
50
100
150
200
250
300
m_{inv} (j,j) GeV
DD_2110

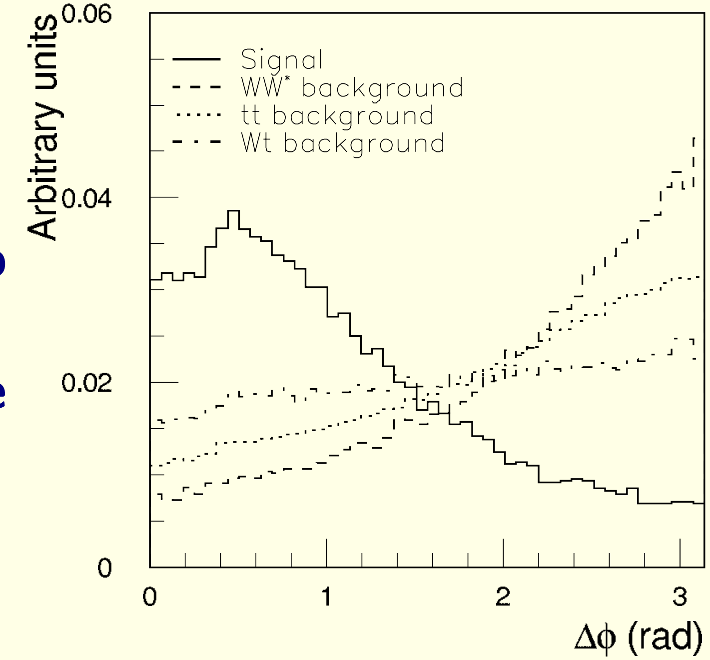
$H \to WW \to \ell\nu\ell\nu$ **much harder**

No mass constraint

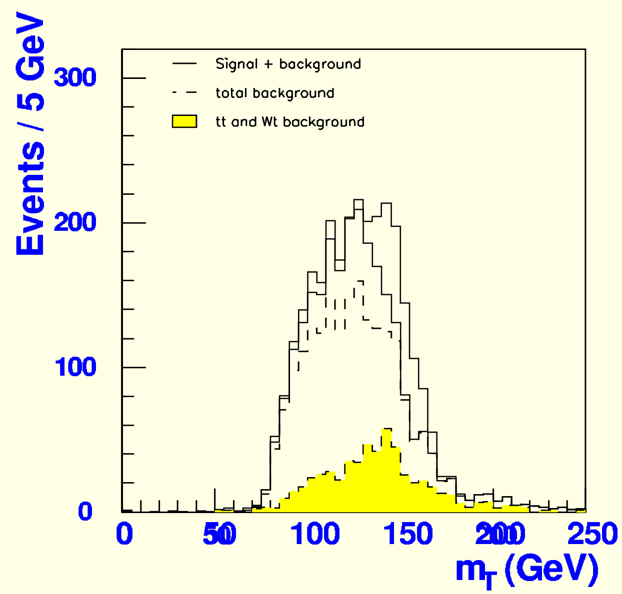
Angular correlation between leptons used to distinguish signal from background

Higgs is scalar: leptons tend to go in same direction

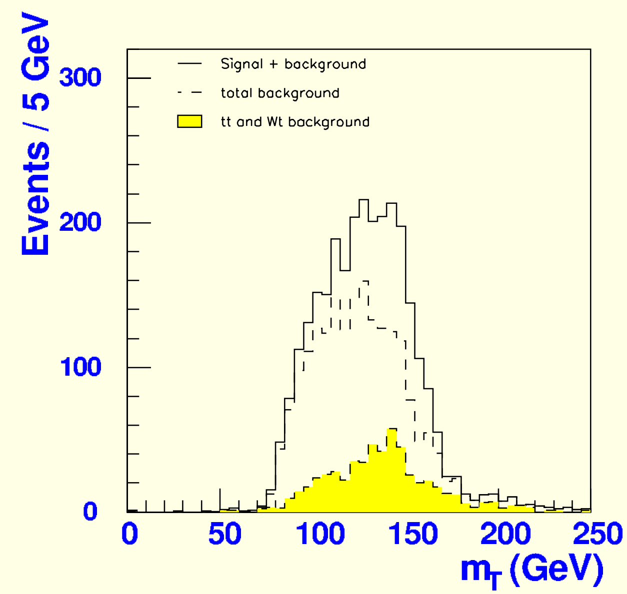
Most useful around 160 GeV: $S/B \sim 2$



Some mass sensitivity from the transverse mass made from leptons and $\not{E}_T$

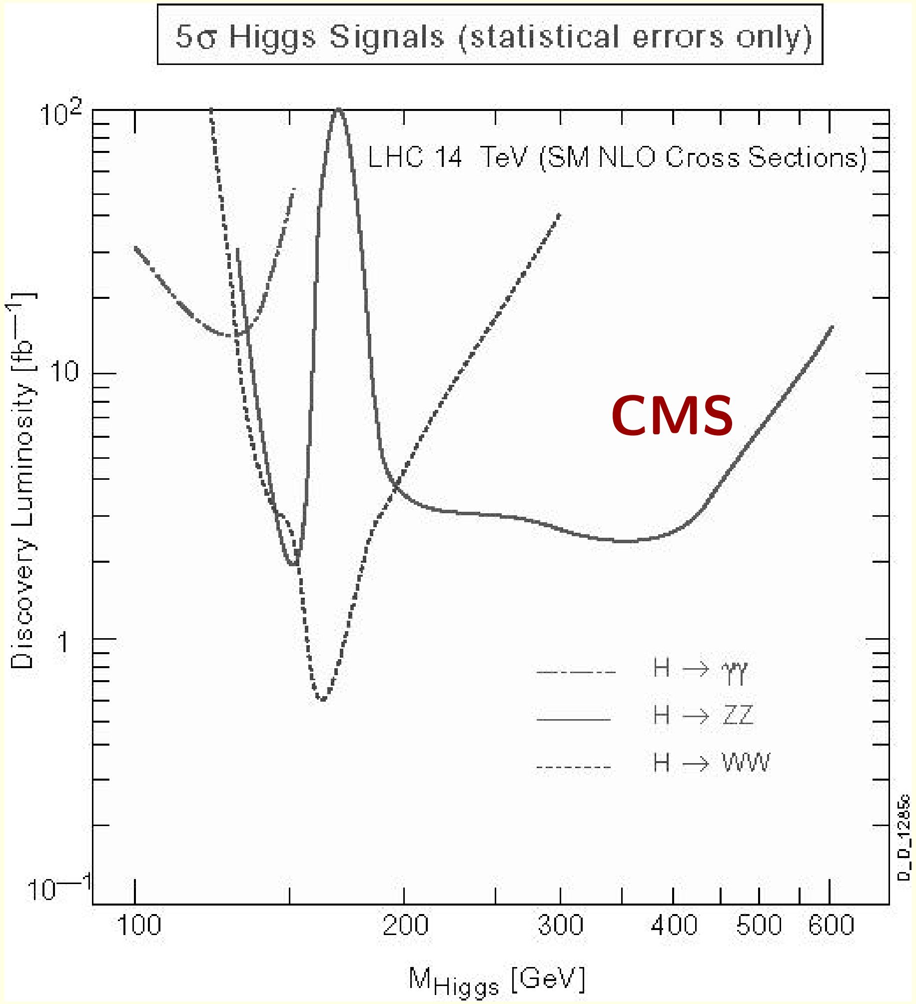


. $M_H = 150$



. $M_H = 170$

Higgs will have been discovered by either LHC or Tevatron before 2008 on current schedule.



Plot shows Luminosity needed for discovery

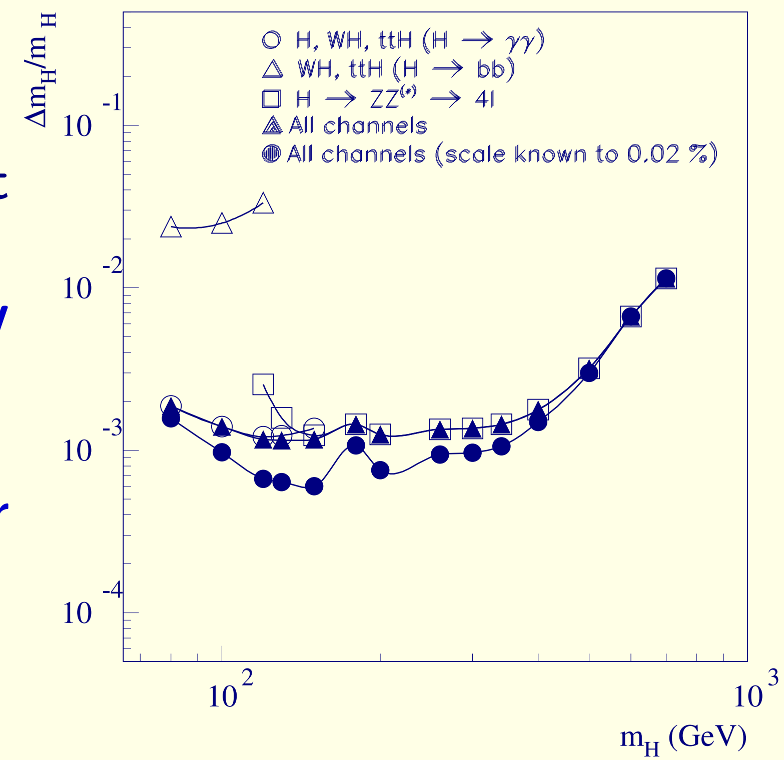
Big Issue is what measurements will be available?

Precision on mass is limited by resolution at small mass and Higgs width at large mass

If you see it, mass is measured accurately (except for WW mode)

Error is $< 0.1\%$ at small mass

Intrinsic width too small to measure for $M_H \lesssim 350\mathrm{GeV}$



Observable channels depend on mass

$gg \to H \to \gamma\gamma$: $80 < M_H < 135$

$gg \to H \to ZZ \to 4\ell$: $120 < M_H < 700$

$gg \to H \to ZZ \to \ell\ell\nu\nu$: $250 < M_H < 1000$

$gg \to H \to WW \to \nu\ell\nu\ell$: $140 < M_H < 190$

$gg \to H \to WW \to \nu\ell \mathrm{jetjet}$

$300 < M_H < 1000$

$q\bar{q} \to W/Z/t\bar{t}(\to \ell + X)H(\to \gamma\gamma)$

$100 < M_H < 130$

$q\bar{q} \to W/Z/t\bar{t}(\to \ell + X)H(\to b\bar{b})$

$100 < M_H < 125$

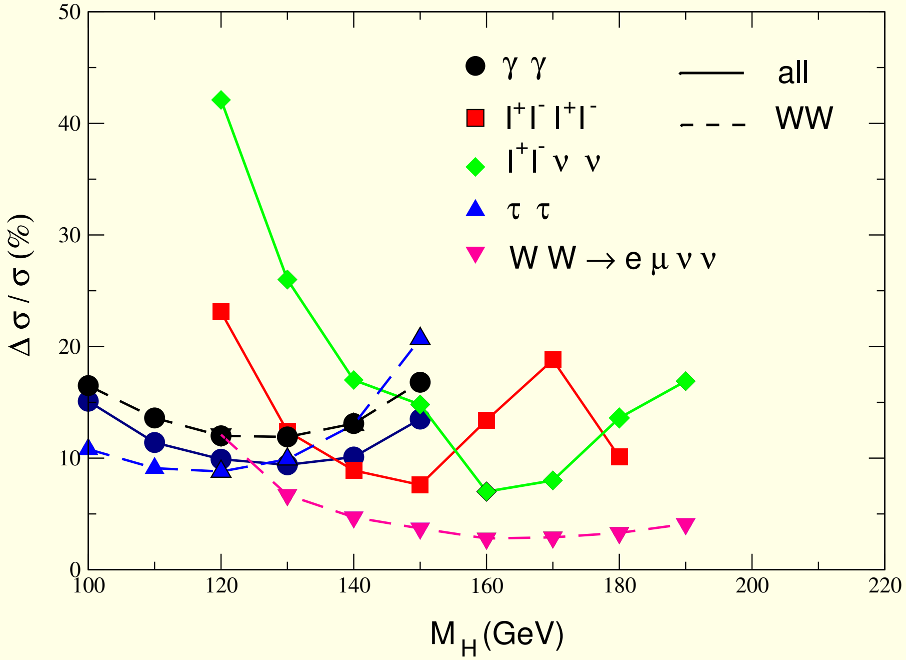
$qq \to qqH(\to \tau\tau)$: $100 < M_H < 150$

$qq \to qqH(\to \gamma\gamma)$: $100 < M_H < 140$

$qq \to qqH(\to WW \to \ell\ell\nu\nu)$

$130 < M_H < 190$

Precision on rates



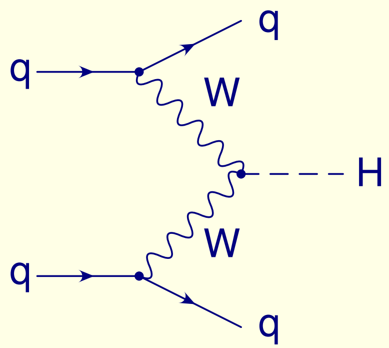
For larger masses only WW and ZZ available.

If same production process is used then ratios of couplings can be obtained directly *e.g.* $\boldsymbol{\Gamma(\tau\tau)/\Gamma(WW)}$ **for** $M \sim 140$ GeV

Otherwise measurements depend on theory of production process.

$\boldsymbol{qq \to qqH}$ `vital`

$qq \to qqH$



Vital at large masses where it dominates production
Will provide valuable information at smaller masses where it is $\sim 10\%$ of rate. Measures WWH coupling

Must be extracted from background and main Higgs process
Exploit forward jets and quiet central region
Final states $\gamma\gamma$ $e\mu\nu\nu$ and $\tau\tau$ can be reconstructed.

Event rates for $M_H = 140\mathrm{GeV}$ and $100\mathrm{fb}^{-1}$

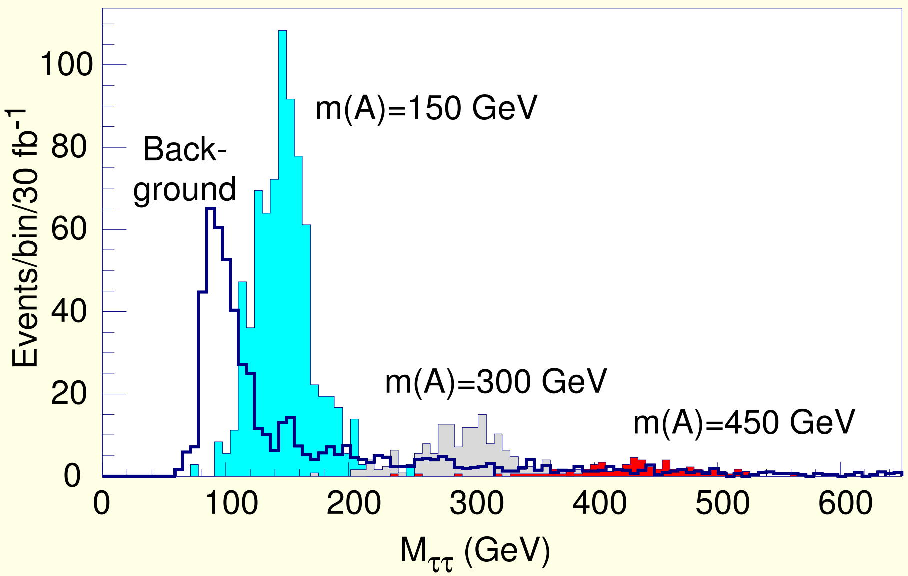
Process	Signal	Background
$\gamma\gamma$	53	51
WW	296	96
$\tau\tau$	79	27

P_T of Higgs $\sim M_W$: $\not{E}_T$ enables $\tau\tau$ mass to be reconstructed
Hence $\gamma\gamma$ and $\tau\tau$ have a mass peak

More studies are underway

MSSM Higgs

New channels become available such as $A \rightarrow \tau\tau$



Uses $\tau\tau \rightarrow \ell\nu\nu_\tau h\nu_\tau$
Observed τ **decay products determine** τ **direction**
Missing E_T **enables** $\tau\tau$ **mass reconstruction** $\Delta M/M \sim 10\%$
Background is dominated by real $\tau' s$ **not QCD jets**

Higgs production rates could be much bigger if it can be produced in the decay of something else such as squark or gluino

$H^+ \to \tau\nu$

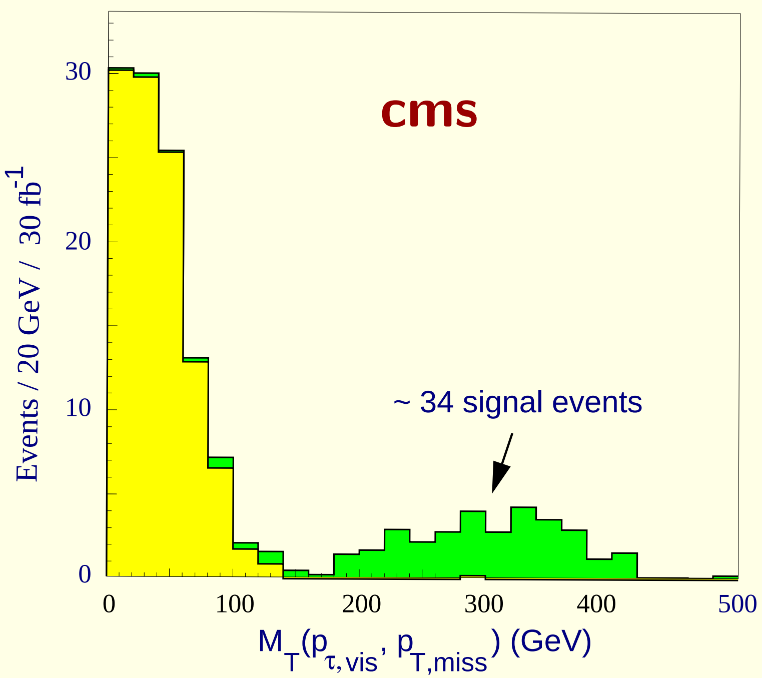
BR not small; $M_{H^+} = 400\ \text{GeV}$**,** $\tan\beta = 30$**; BR=14%**

Production via $gb \to Ht$**;** $\sigma(H^+t)\ \sim 1\ \text{pb}$

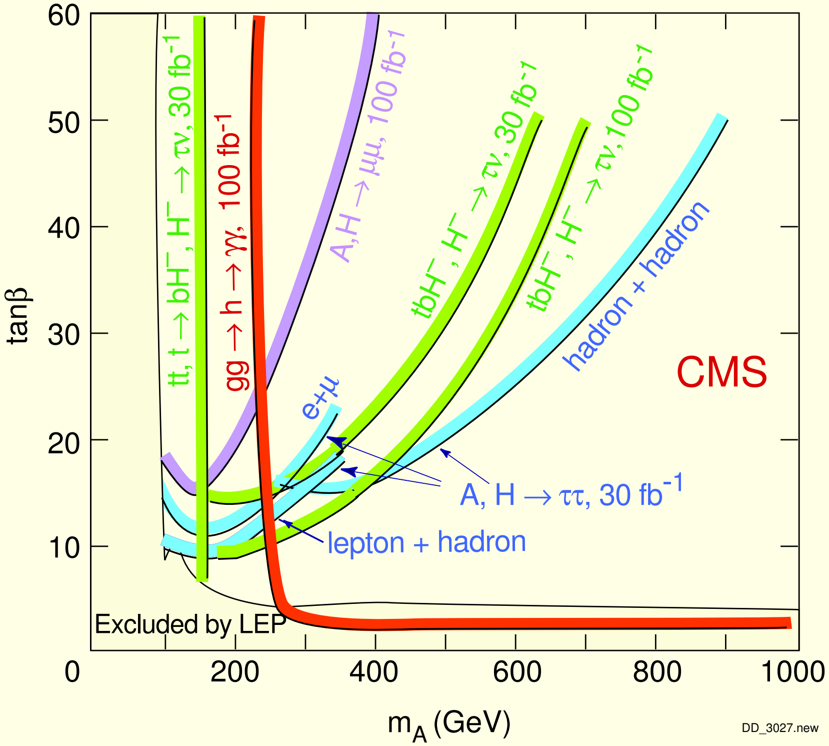
Use single prong hadronic tau decay ($p_T > 100$ **GeV), plus jets and missing** E_T **(**$> 100\ \text{GeV}$**)**

Reconstruct top from jjb**,** $m(jj) = M_W \pm 25$**,** $m(jjb) = M_t \pm 25$

Signal is in transverse mass of "τ**" and missing** E_T



Plot has $M_{H^+} = 409$ **and** $\tan\beta = 40$



Note that this is 5σ not 95% exclusion

$A \to \tau\tau$ exclusion is ~ 450 GeV at $\tan\beta = 10$

Region at large M_A where only $h \to \gamma\gamma$ is seen

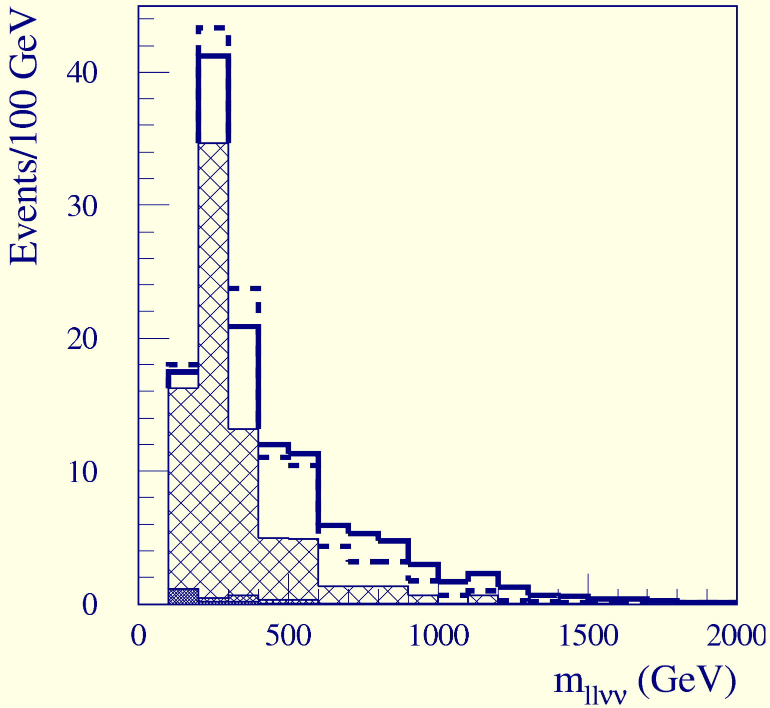
Beware of too literal an interpretation

Other measurements such as $H/A \to \tilde{\chi}_0^2\tilde{\chi}_0^2$ may give more measurements in the large M_A region

Strongly coupled WW

Simplest models have few signatures.
K-matrix produces excess of events in WW at large mass: No mass peak so signal is hard to extract.
W^+W^+ is cleanest final state
Two isolated positive leptons with $M(\ell\ell) > 100$ GeV
≤ 3jets two of which have $|\eta| > 2$

Plot shows mass of $\ell\ell \not{E}_T$
Event rates are small $S/B \sim 50/75$ for 300 fb^{-1}
Should be possible to establish signal, but measurements will be hard



Resonant models are easier

Comment on Little Higgs

Minimal ingredients of Little Higgs model are

- **New quark with mass below 2 TeV (approx) decaying to Zt and ht.**

- **New gauge bosons with mass below 5 TeV (approx).**

Both of these should be accessible at LHC (detailed studies underway)
Will need constraints from Precision EW tests at NLC.

Upgrades?

Physics studies carried out in Summer 2000 and 2001 in response to request from CERN management.

Joint study report available hep-ph/0204087

Addressed physics impact of Luminosity and energy upgrades. $\mathbf{28}\mathrm{TeV}$ and $\mathbf{10}$ times design luminosity. Luminosity upgrade is inexpensive and technically feasible now.

I would guess that a luminosity upgrade could happen 6 years after turn on, could be on same time scale as NLC

Machine issues

Ultimate Luminosity of 2.3×10^{34} could be achieved by current design but only in two experiments (ATLAS+CMS)

Further increases need mixture of

- Reduced bunch spacing – continuous beams?. Difficult for Experiments (12.5 ns is working number)
- new $low - \beta$ quads; design exists
- smaller β^* or reduced bunch length;
- larger beam intensity; Needs new proton linac and booster or 2.2 GeV high power linac (could be useful for muon collider)
- New separation dipoles inside experiments.

Energy upgrade is much more expensive; 16 Tesla dipoles. Proof of principle exists

Detector Performance

Luminosity is much more demanding

EM-cal performance degrades: 30 GeV electrons $\frac{\sigma}{E} \sim 2.5\%$ at 10^{34} $\longrightarrow \frac{\sigma}{E} \sim 3.6\%$ at 10^{35}

b-tagging

Rejection factors against u-jets
for 50% b-tagging efficiency

P_T(GeV)	10^{34}	10^{35}
25-40	33	3.7
45-60	140	23
60-100	190	27
100-200	300	113
200-350	90	42

e/jet separation: 40GeV E_T

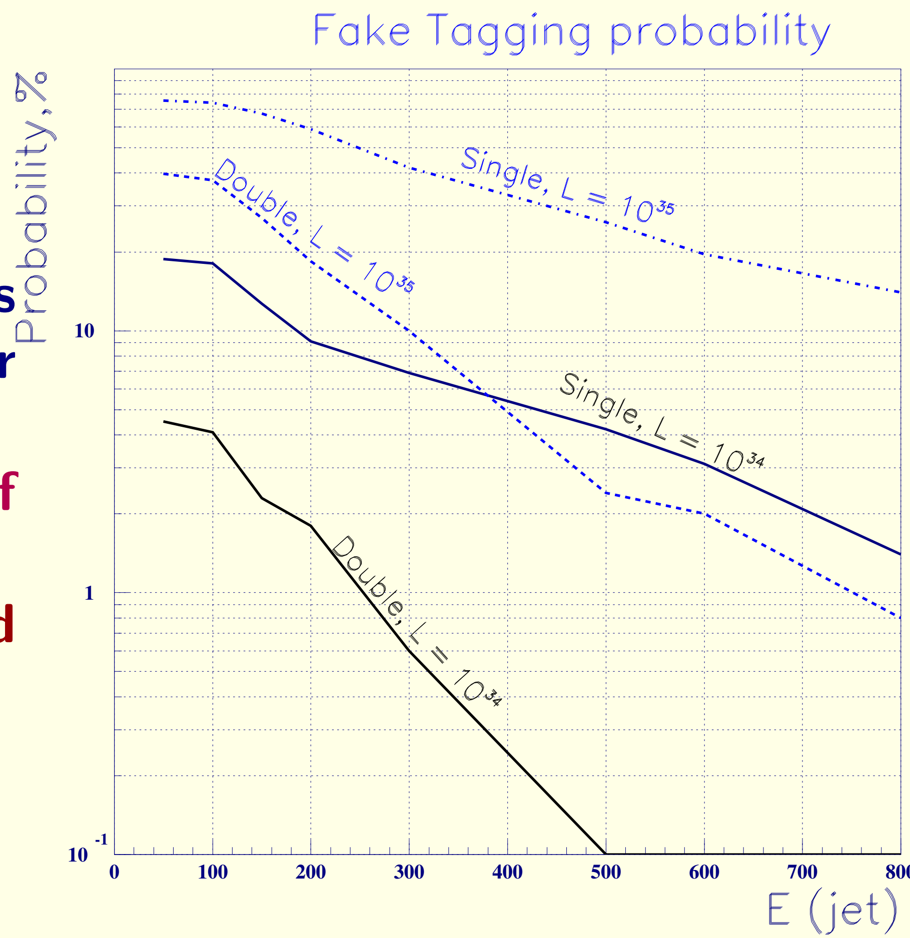
	Electron effic.	Jet Rejection
10^{34}	81%	10600 ± 2200
10^{35}	78%	6800 ± 1130

Jet Tagging/vetoing at High Luminosity

Tagging of jets at $|\eta| > 2$ provides powerful background rejection for some physics processes

Preliminary full simulation study of fake tag rates from pile-up

Not optimized: More studies needed



Strongly coupled WW with upgrade

Rate limited so will benefit strongly.

Note that tagging/vetoing do not scale from normal luminosity, so some advantage is lost

Signal in W^+W^+ to leptons is shown together with significance

Model	300 fb^{-1} 14 TeV	3000 fb^{-1} 14 TeV	300 fb^{-1} 28 TeV	3000 fb^{-1} 28 TeV
Background	7.9	44	20	180
K-matrix Unitarization	14	87	57	490
Significance	3.0	7.6	6.5	18.9
Higgs, 1 TeV	7.2	42	18	147
Significance	1.8	4.5	2.9	8.1

Note "1 TeV Higgs" is not sensible, its for comparison only.

New Decay modes of Higgs

$H \to Z\gamma$. Comparable BR to $H \to \gamma\gamma$ but only leptonic Z decays can be used. With $6000\mathrm{fb}^{-1}$ signal is measurable over same mass range as $H \to \gamma\gamma$.

$H \to \mu^+\mu^-$ Full potential of an luminosity ($6000\mathrm{fb}^{-1}$) upgrade makes this visible.

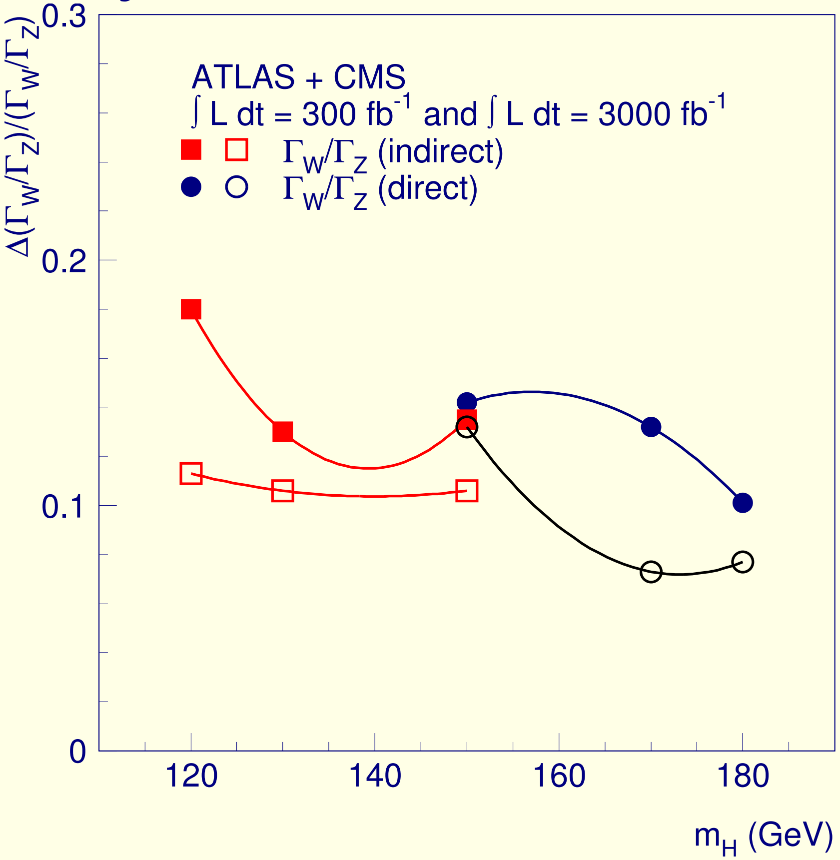
m_H (GeV)	$S/\sqrt{B}$	$\frac{\delta\sigma\times\mathrm{BR}(H\to\mu\mu)}{\sigma\times\mathrm{BR}}$
120 GeV	7.9	0.13
130 GeV	7.1	0.14
140 GeV	5.1	0.20
150 GeV	2.8	0.36

Measurements of Higgs Couplings

Luminosity upgrade improves precision by up to a factor of two

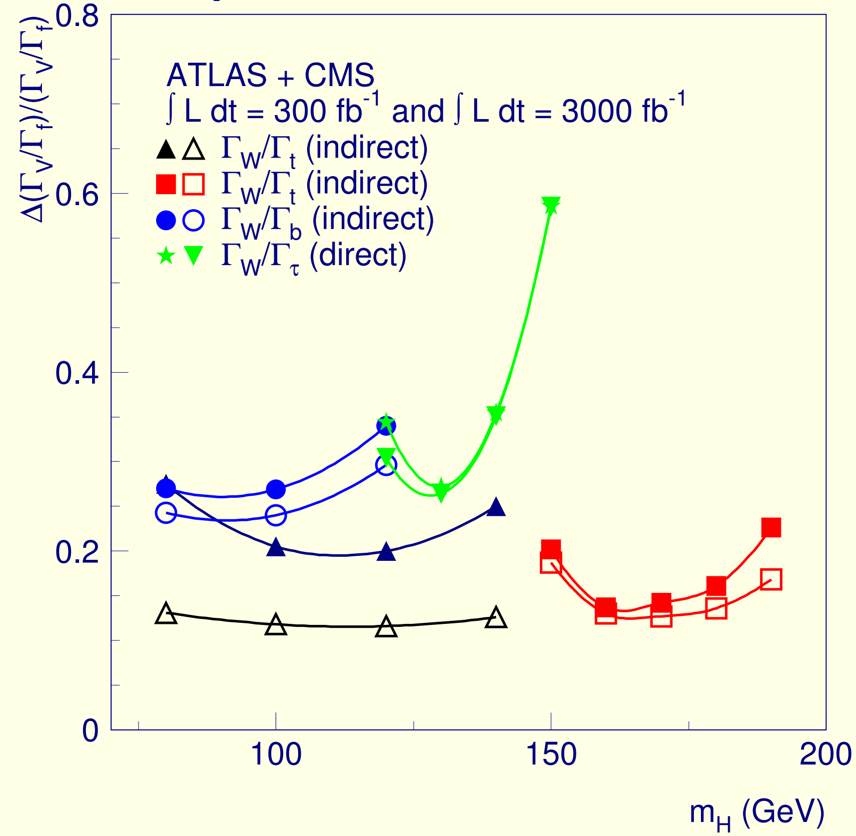
Boson couplings

Measured from $\gamma\gamma$ WW and ZZ decays



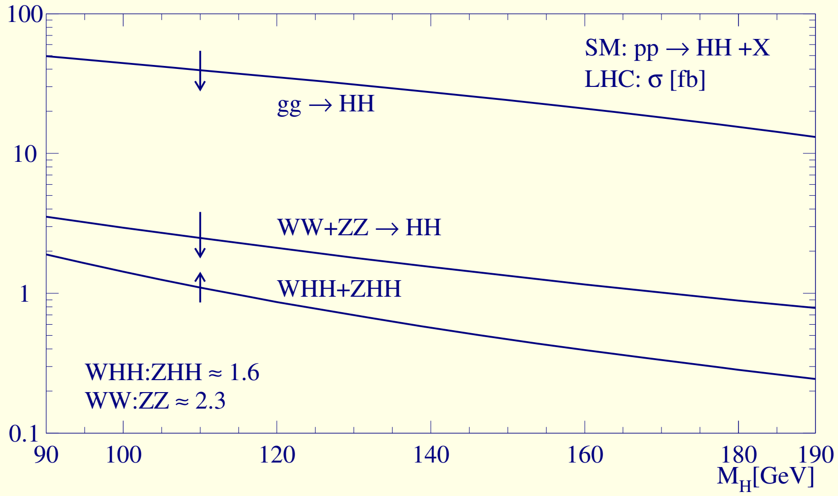
Fermion couplings

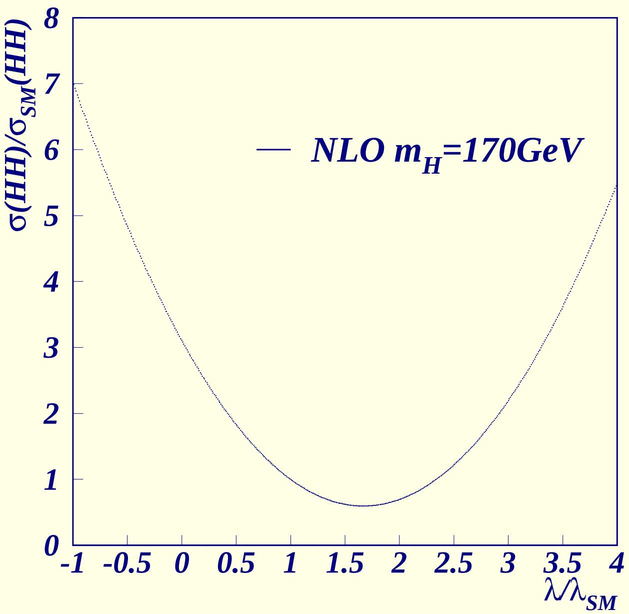
Inferred from $\gamma\gamma$ and WW final states and comparison of WH, $t\bar{t}H$ and H production



Higgs self coupling??

Preliminary particle level study of HH final states which contains a contribution from λ_{HHH} Very hard to measure anywhere: NLC is about 20% precision.
Hopeless without an upgrade.

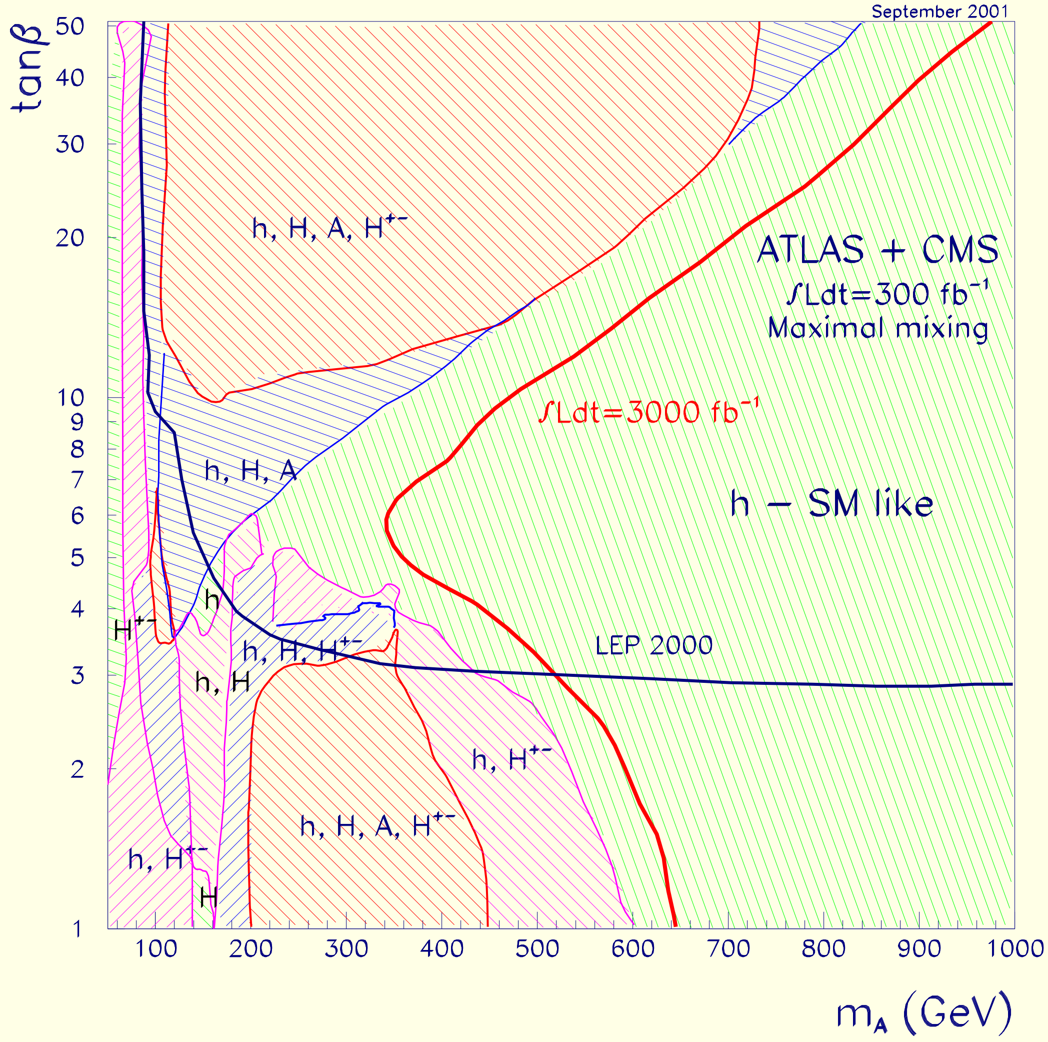




Best possibility is $gg \to HH \to 4W \to \ell^+\ell^+\nu\nu 4j$
Event rates for $6000\mathrm{fb}^{-1}$ small. Only works if $M_H \sim 180GeV$
$S/B \sim 350/4150$
If backgrounds can be measured/constrained then $\Delta\lambda/\lambda \sim 0.25$

MSSM Higgs

In the *green region* only h is observable (unless SUSY decays to Higgs increase rates)



Region shrinks with more luminosity
Covers most of region that 500 GeV LC can reach indirectly via precision measurements of light Higgs couplings
Note this this is 5σ not exclusion

Triple Gauge couplings

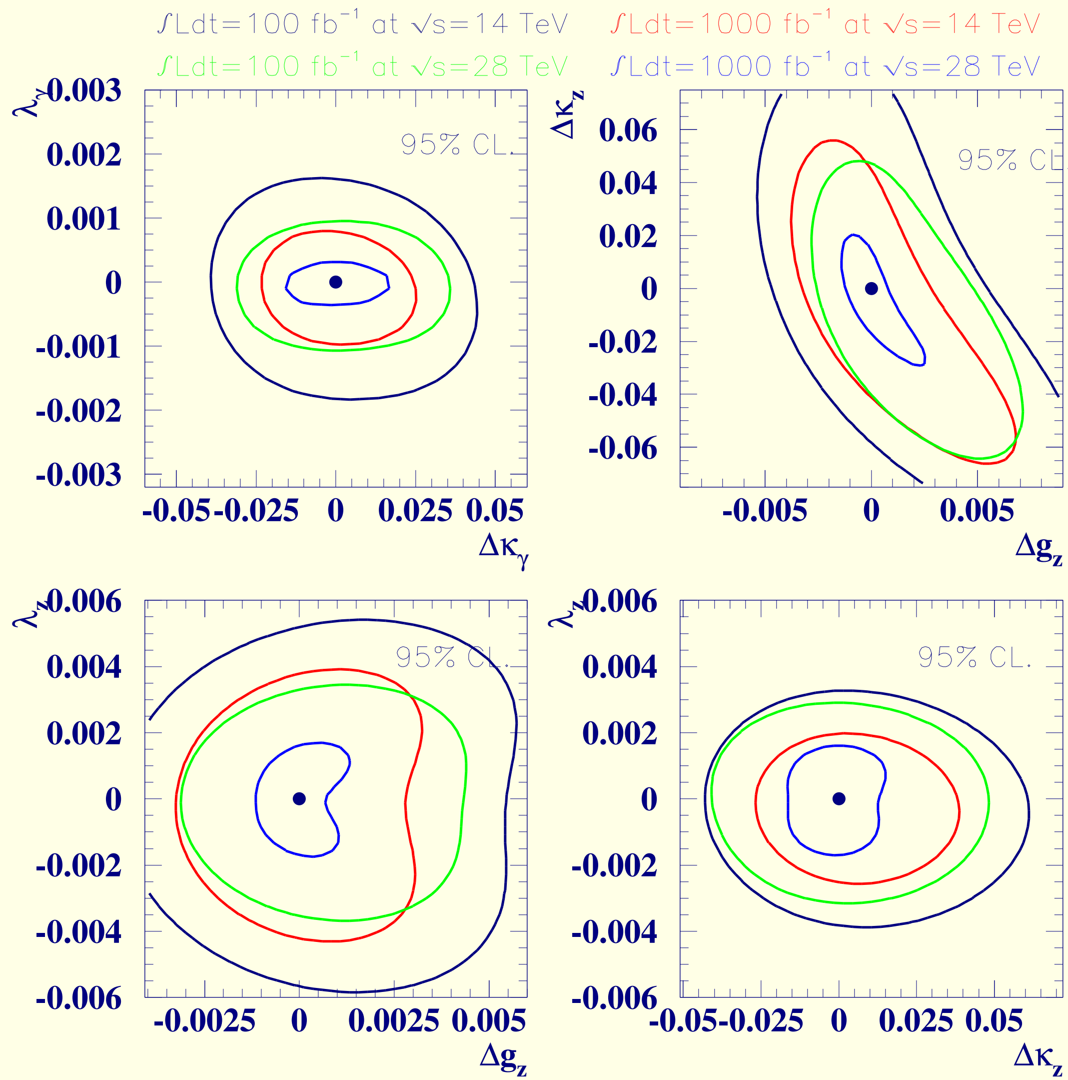
Using WZ and $W\gamma$

Note that Luminosity is more effective than Energy

Only μ, ν, γ final states included at higher luminosity

Electrons could be added with upgraded tracker

Competitive with 500 GeV Linear Collider for $\lambda_{\gamma,Z}$



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Multi Z/W Production

In fully leptonic final states with $6000\ \mathrm{fb}^{-1}$ (ATLAS+CMS). Both e and μ included.

Process	Events
$W^+W^+W^-$	2600
W^+W^-Z	1100
$W^\pm ZZ$	36
ZZZ	7
$W^+W^+W^-W^-$	5
$ZW^+W^-W^\pm$	1

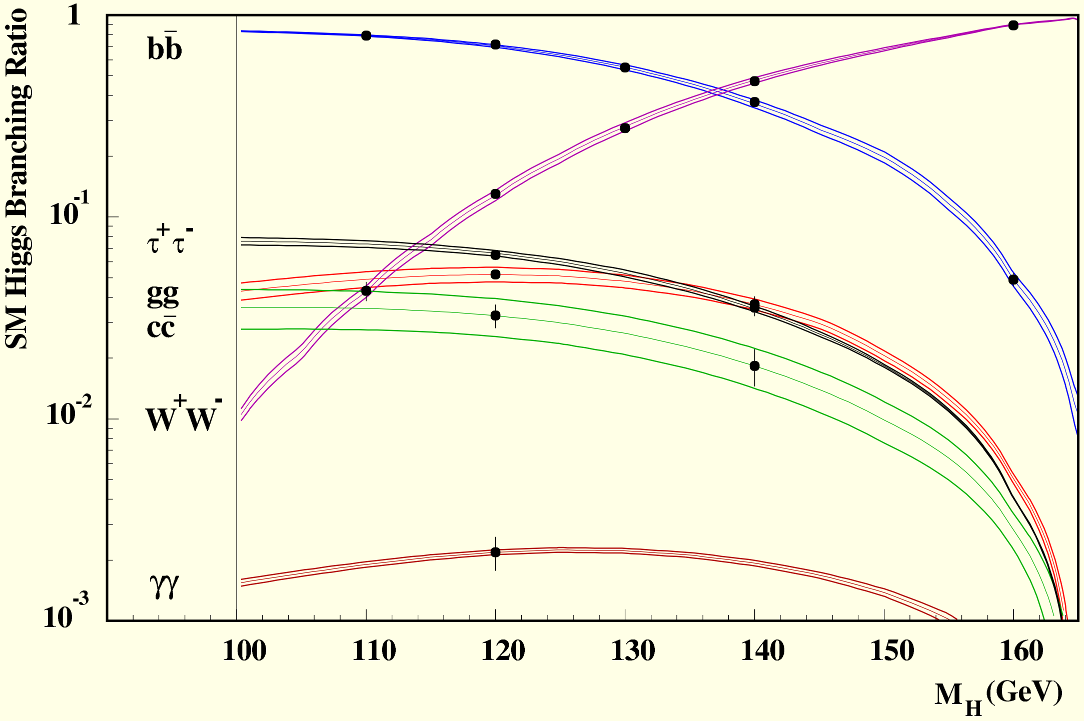
$m_H = 120$ **assumed; rates are larger for 200 GeV**

Note that only first two are observable at standard LHC

Constraints on quartic couplings possible; these cannot be probed without upgrade when W is off shell timelike

What we need the linear collider for

- Better precision on branching ratios and observation of modes such as $H \longrightarrow c\bar{c}$ that are not possible at LHC



- Elucidation of MSSM Higgs sector. Sector may be non-minimal and observation of all states will eventually be required. LHC will not be able to do this. While indirect constraints will be useful, NLC will need to be above threshold for big impact

- Precision measurements will be vital to constrain new physics, particularly if

LHC has already seen some new particles which affect the prediction in a well defined way.

- **Strongly coupled scenarios need all the help they can get. LHC is limited here. NLC energy upgradability is vital.**

Two extreme situations

Higgs is almost standard model like. Here precision is everything and luminosity is vital.

Non-Standard Electroweak physics. Will need to observe the new states and energy upgradability is more important.